

Miniaturized, Flexible Electroosmotic Device Based on Laser-Patterned PEDOT:PSS Electrodes for Drug Delivery and Electrophysiological Biosensing

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Summary:

Electroosmotic micropumps use electric fields to precisely control fluid flow in microdevices. They are attractive for implantable bioelectronic devices due to their simple electrode-based design and compatibility with miniaturization. This study presents a low-voltage bioelectronic pumping and sensing device with thin-film interdigitated electrodes achieving very low flow rates (~ 0.5 nL/min). Laser-fabricated designs and simulations optimize flow and reduce vortices. PEDOT:PSS improves efficiency and electrode stability. A flexible implantable prototype demonstrates potential for biomedical applications like drug delivery and electrophysiological biosensing, specifically for the treatment of neurological disorders.

Keywords: bioelectronics, drug delivery, electrophysiology, flexible, implantable.

Background, Motivation and Objective

Electroosmotic (EO) actuators are suitable for microfluidic applications because they can produce high pressures and precise flow. In these devices an electrolyte is pumped by applying an electric field to the Debye layer, which is formed by the ions due to electric screening of the immobile charges on the walls of the liquid channels within the pump [1, 2]. The EO pumping mechanism is one of the simplest ones for fluidic control, since it is based only on electrode arrays, therefore it is very suitable for the design and fabrication of bioelectronic implantable micro-devices with applications in drug delivery or biofluid sampling [3]. Currently, these pumps are designed to trigger large flow rates ($\sim 1\text{--}10$ $\mu\text{L min}^{-1}$), they are based on thick electrodes and their sizes are mostly not compatible with miniaturized advanced bioelectronics.

In this work, we aim to design and characterize an AC electroosmotic micropump based on thin-film interdigitated electrodes, as a proof-of-concept prototype capable of generating ultra-low flow rates while operating at significantly reduced voltages. The objective is to demonstrate a scalable and efficient platform for controlled fluid delivery in biomedical applications, where drug delivery and biofluid sampling can be coupled with electrophysiological biosensing.

Description of the Methodology

An AC electroosmotic micropump based on asymmetric thin-film interdigitated electrode (IDE) designs is developed. Different AC

electrical waveforms are applied to drive the flow of a phosphate buffer solution (PBS) containing $1\text{ }\mu\text{m}$ polystyrene microbeads, enabling optical visualization of fluid motion. The pumps are characterized in vitro using microfluidic channels with sub- $50\text{ }\mu\text{m}$ dimensions, fabricated through PDMS replica molding from laser-patterned metal molds. IDEs with both symmetric and asymmetric configurations are patterned using nanosecond and femtosecond pulsed lasers on thin films of gold (Au) and PEDOT:PSS deposited by DC sputtering. The laser microfabrication provides an ultra-fast, effective and maskless method to pattern thin films deposited by DC sputtering. The resolution offered by different pulse durations is used to design IDEs within a wide range of dimensions, from $10\mu\text{m}$ to $100\mu\text{m}$ trackwidth. Finite-element-modelling (FEM) simulations are used to predict the fluid dynamics due to electroosmosis, systematically showing a strong dependence on the flow rate on the electrode designs and the microfluidic channels size. Additionally, it is possible to predict the formation of fluidic vortices in the gaps between the electrodes or above each electrode. Tuning the channel height, the trackwidth and the inter-electrode gaps contributes to regulate more uniformly the fluid flow.

Results

Simulations reveal a strong dependence of flow rate on electrode geometry and microchannel dimensions, and predict vortex formation that can be mitigated through design optimization.

The contribution of the organic conductive material (PEDOT:PSS) is two-fold. First, PEDOT:PSS significantly increases the effective electrode capacitance due to its mixed ionic–electronic conductivity and volumetric charge storage capability. Unlike bare metal electrodes, where capacitance is limited to the electric double layer, PEDOT:PSS enables additional capacitive contributions within its bulk, effectively behaving as a distributed network of nanoscale capacitors [4, 5]. This enhanced capacitance reduces the electrode impedance and allows efficient charge transfer at lower applied voltages, thereby decreasing the voltage required to achieve a given electroosmotic flow rate.

Second, PEDOT:PSS improves the stability and durability of gold (Au) electrodes under electrical operation. The polymer coating reduces electrode polarization and increases the charge injection capacity, mitigating electrochemical degradation processes that typically occur at higher voltages [6]. Additionally, PEDOT:PSS exhibits excellent electrochemical stability and strong adhesion to Au surfaces, forming a protective interface that limits corrosion and prolongs electrode lifetime in electrolyte environments [7].

In vitro experiments enable to quantify the dependence of the resulting flow rate and the applied voltage amplitude, the AC driving frequency, the applied DC offset and the electrode design. Flow rates in the order of $\sim 0.5 \text{ nL min}^{-1}$ can be achieved with ultra-low peak-to-peak voltages ($\sim 0.8\text{--}3 \text{ V}$) (Fig.1).

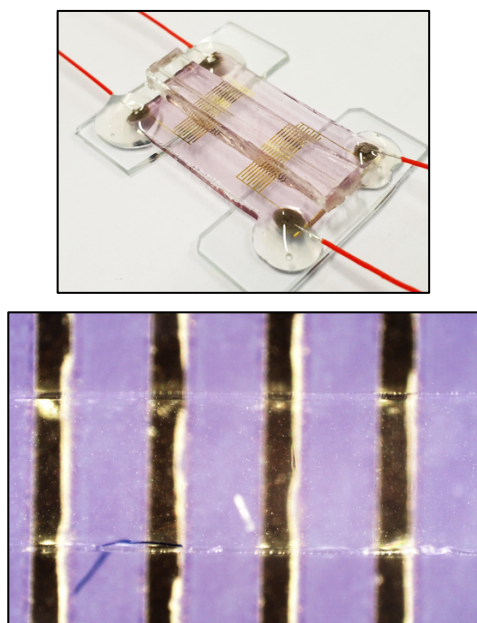


Fig. 1. Top: In vitro platform to test the PEDOT:PSS based electrodes with a PDMS microfluidic channel. Bottom: optical micrograph showing the microbeads flowing at a speed of $\sim 0.5 \text{ nL min}^{-1}$ within a microfluidic channel filled with PBS on top of interdigitated electrodes.

Additionally, a flexible proof-of-concept AC electroosmotic pump, designed in the form of an implantable probe (Fig.2), is successfully demonstrated and tested in vitro in an agarose gel phantom.

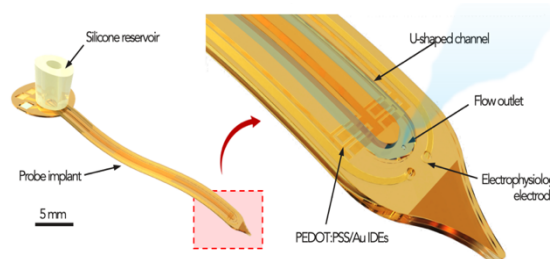


Fig. 2. Illustration of a flexible pump based on the PEDOT:PSS/Au electrodes for drug delivery and electrophysiological biosensing.

Conclusions

The proposed PEDOT:PSS-based electroosmotic pumps pave the way for the realization of implantable bioelectronic probes for biomedical applications, in particular for the treatment of neurological disorders (e.g., epilepsy, Parkinson's disease, chronic pain, etc.). Designs with arrays of multiple pumps are envisioned for more complex and sophisticated microfluidic systems for fluid control and biosensing.

References

- [1] Guy RH, Kalia YN, Delgado-Charro MB, et al. Iontophoresis: electrorepulsion and electroosmosis. *Journal of Controlled Release* 2000; 64: 129–132.
- [2] Kusama S, Sato K, Matsui Y, et al. Transdermal electroosmotic flow generated by a porous microneedle array patch. *Nat Commun* 2021; 12: 658.
- [3] Mariello M, Eş I, Proctor CM. Soft and Flexible Bioelectronic Micro-Systems for Electronically Controlled Drug Delivery. *Advanced Healthcare Materials*; n/a: 2302969.
- [4] Calabia Gascón N, Terryn H, Hubin A. The role of PEDOT:PSS in (super)capacitors: A review. *Next Nanotechnology* 2023; 2: 100015.
- [5] Kauth A, Wegener J, Jiang H, et al. PEDOT:PSS Electropolymerization Protocol for Microelectrodes Enabling Low-Cost Impedance-Based Cellular Assays. *Applied Research* 2025; 4: e202400087.
- [6] Pranti AS, Schander A, Bödecker A, et al. PEDOT:PSS coating on gold microelectrodes with excellent stability and high charge injection capacity for chronic neural interfaces. *Sensors and Actuators B: Chemical* 2018; 275: 382–393.
- [7] Dijk G, Rutz AL, Malliaras GG. Stability of PEDOT:PSS-Coated Gold Electrodes in Cell Culture Conditions. *Advanced Materials Technologies* 2020; 5: 1900662.